Applied Biotechnology for Transportation Fuels Workshop

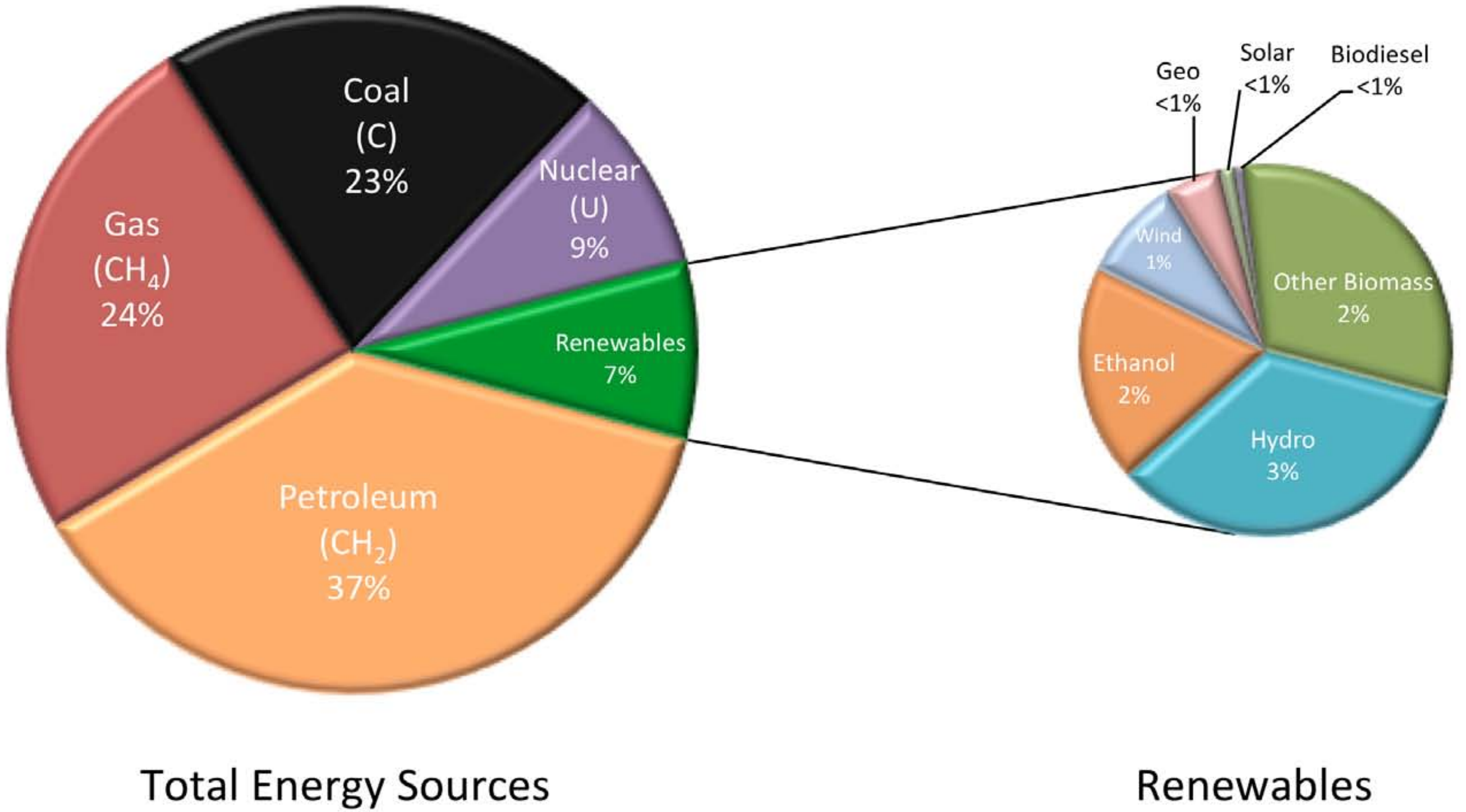
Held December 2-3, 2010

Program Director:
JONATHAN BURBAUM

The laws of thermodynamics

First Law	***You can’t win***
Second Law	***You can’t break even***
Third Law	***You can’t get out of the game***

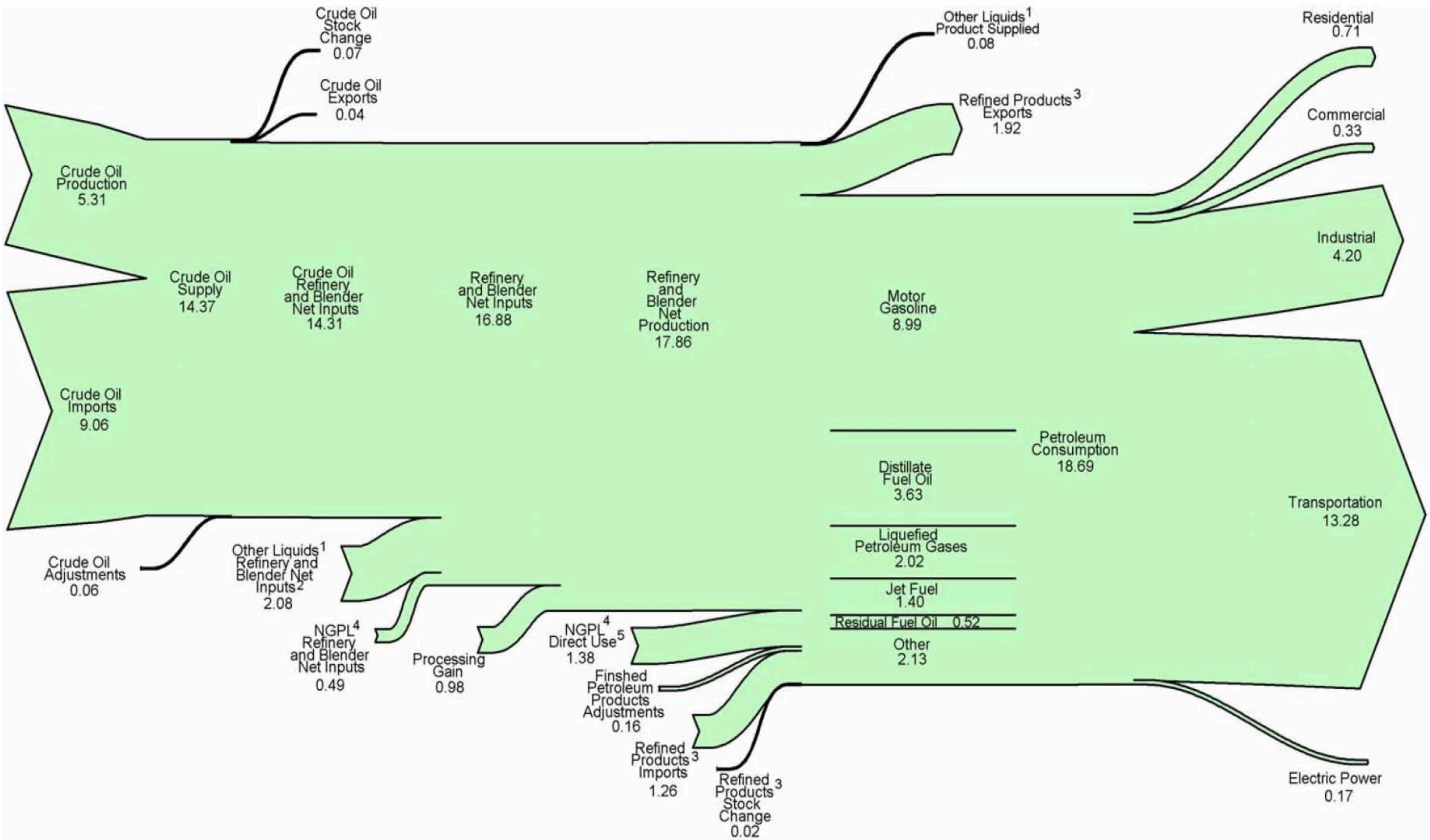
Energy Sources in the US



Source: DOE EIA Annual Review, 2009

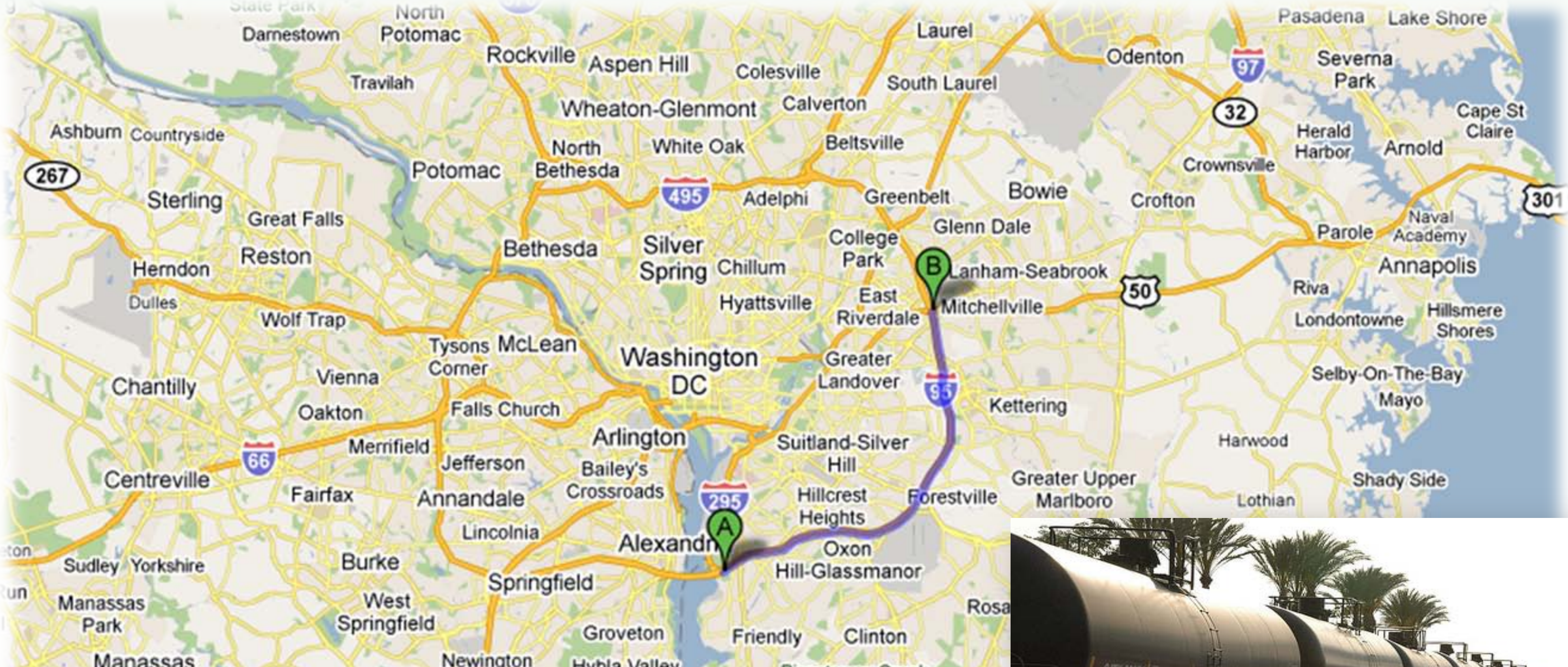
Petroleum Flow in the US: 19 Million Barrels per Day

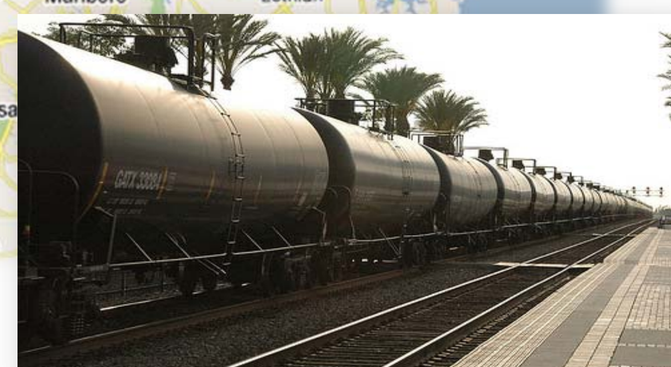
Figure 5.0. Petroleum Flow, 2009
(Million Barrels per Day)



Source: DOE EIA Annual Review, 2009

Scale: What is 1 million barrels?





1460 tank cars…

(685 barrel capacity)

…16.6 miles long

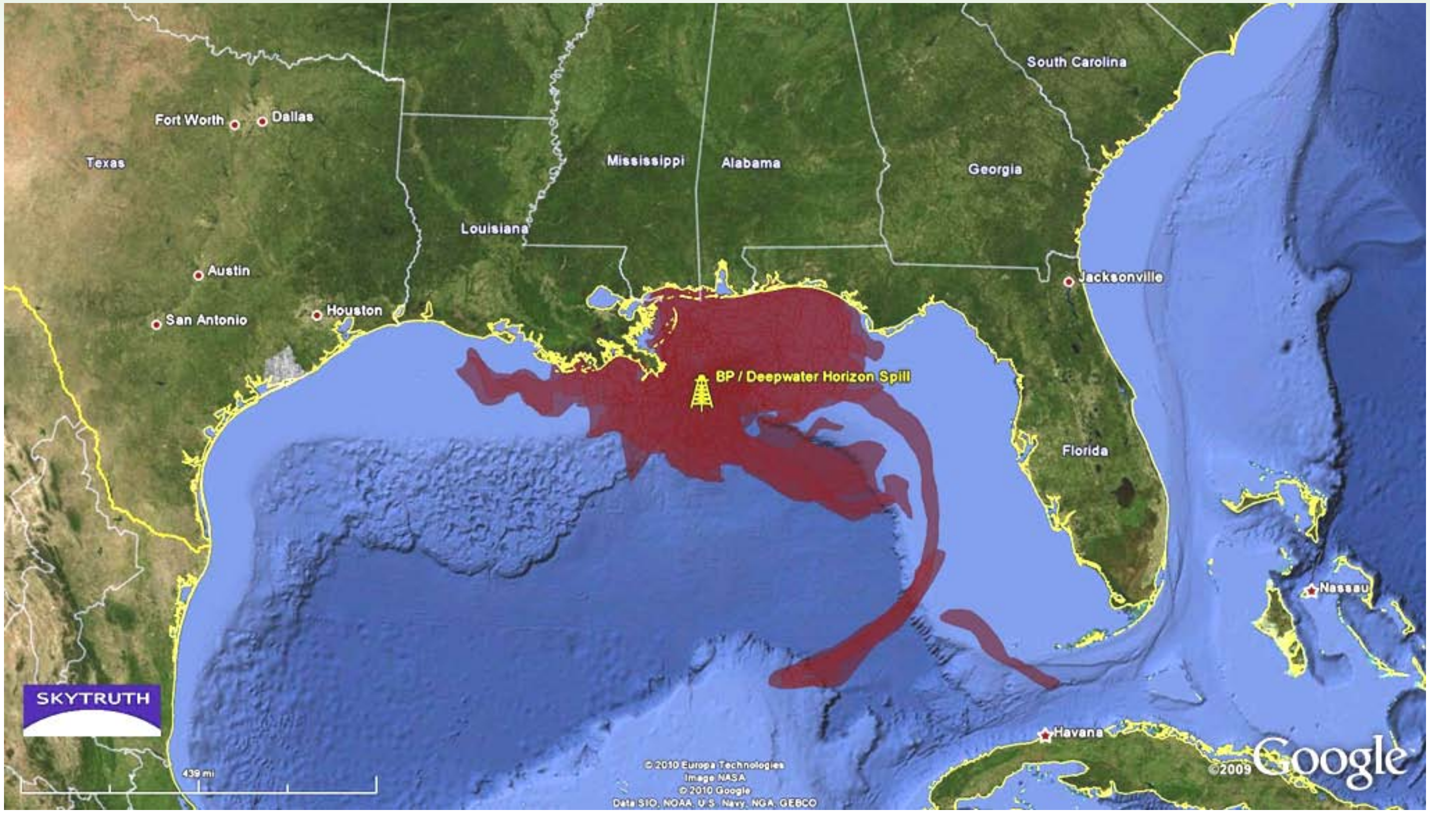
U.S. petroleum demand, 19 Million Barrels per Day

>27,000 tank cars…

(685 barrel capacity)

…>300 miles long

Another Perspective…



- Deepwater Horizon incident
  - 4.9 million barrels of oil spilled
  - ~ 6 hours of domestic use!!

Source: SkyTruth.org; USGS Flow Rate Technical Group

What About Biofuels?

- “Biofuels”: Civilization’s original energy
- Since then, though, a disappointment!
  - Today, biofuels for transportation ~ ethanol
  - Modern biotechnology has had ***NO substantial impact*** on biofuels used for transportation

“Modern” Biotechnology for Biofuels?

1925: The New York Times

FORD PREDICTS FUEL FROM VEGETATION

He Says Electricity Will Heat Cities in the Future—Tells of Testing a New Flour.

BOSTON, Sept. 19 (AP).—The time is coming when Americans will grow their own fuel and American cities will be heated by electricity, Henry Ford is quoted as saying during his stay at his Wayside Inn in Sudbury, in an interview published by The Christian Science Monitor today.

1923:

Patented Jan. 30, 1923. 1,443,881

UNITED STATES PATENT OFFICE.

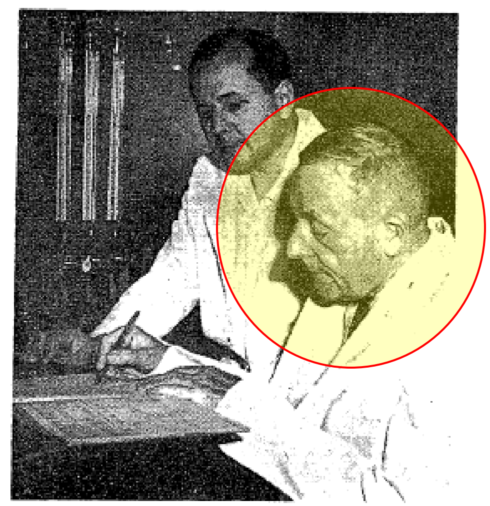
HERBERT LANGWELL, OF STOCKTON-ON-TEES, ENGLAND.

FERMENTATION OF CELLULOSE.

No Drawing. Application filed September 29, 1919. Serial No. 327,265.

1949: The New York Times

Vital Force Found in Plants May Increase World's Food

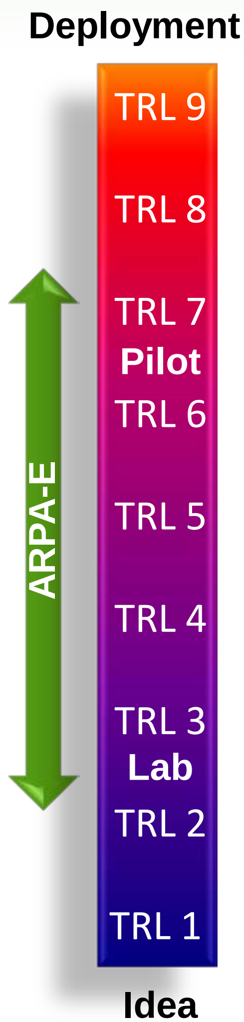


Otto Warburg
Nobel Prize
Physiology, 1931

Scientists, Reporting Efficiency Up to 87% in Using Energy of Sunlight, Visualize 100-Fold Rise in Yield of Algae

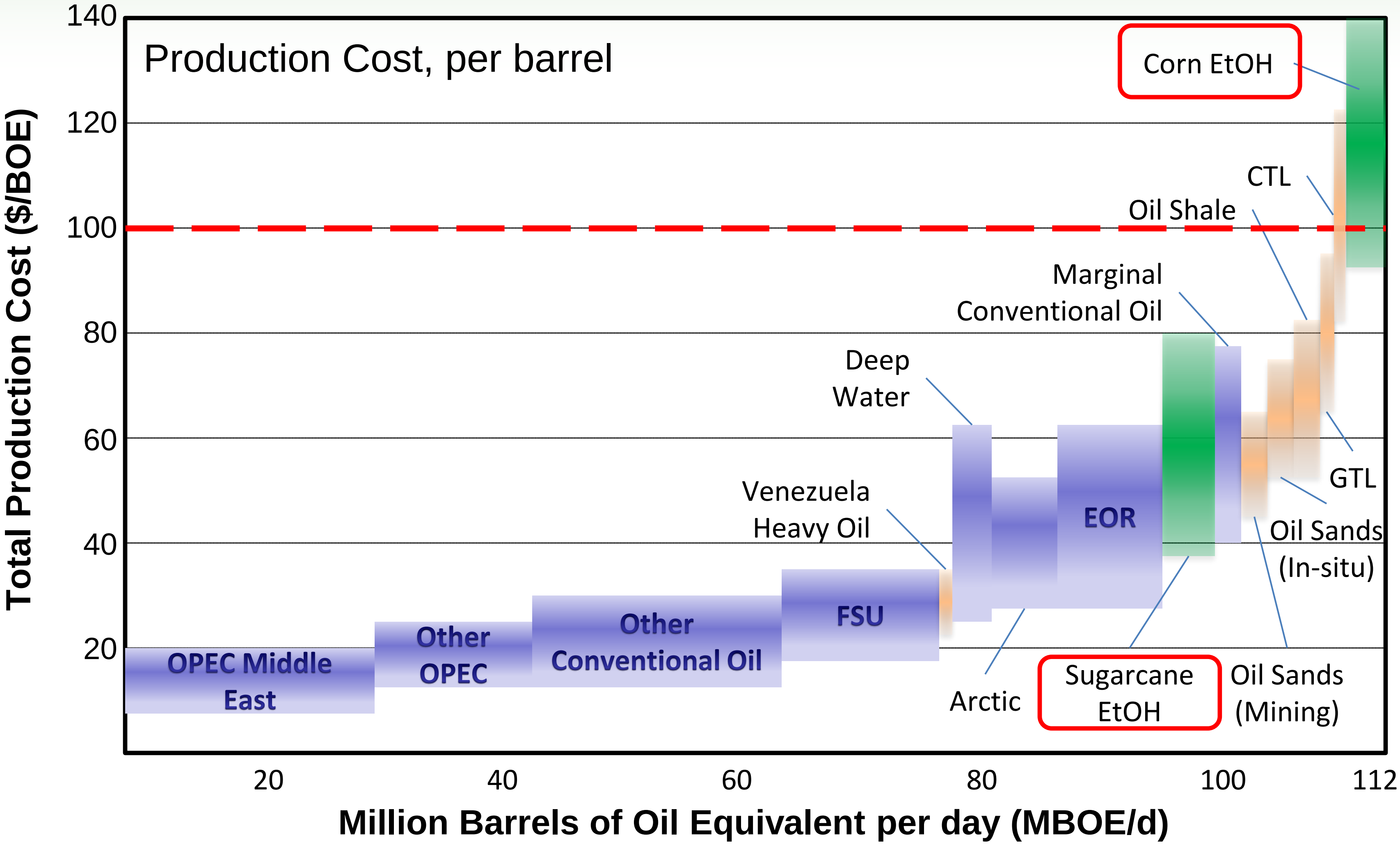
Technology Landscape

Area	Examples	Description	TRL
Repurposed Food Crops	Corn, sugar cane, some oil plants	“Biofuels today”	7-9
Cellulosics	Switchgrass, corn stover	“Feedstock modification”	6-8
Aquatics	Algae, cyanobacteria	“Biofuels tomorrow?”	3-7
Synthetic photobiology	??	“Research”	1-3



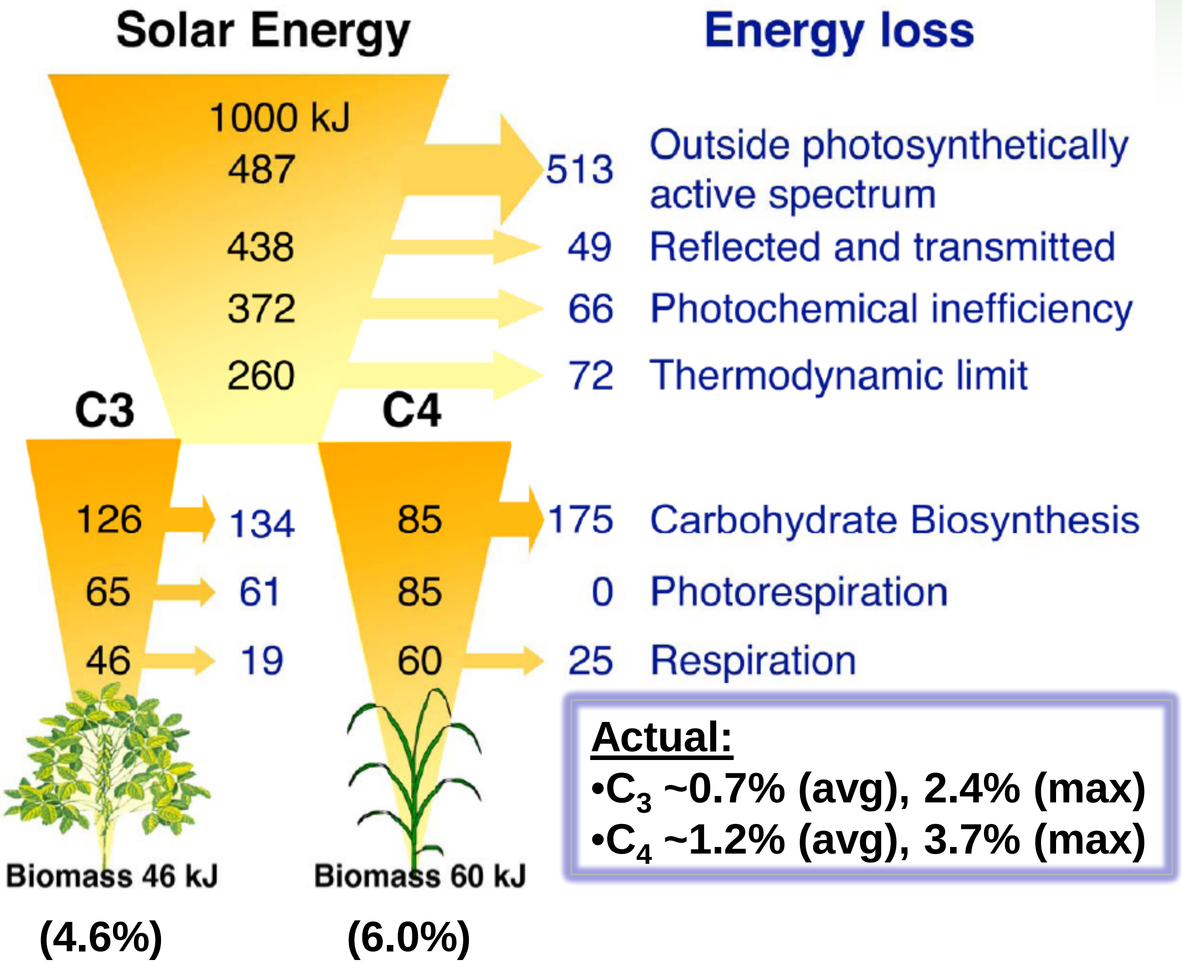
- Next generation biofuels manufacturers seek “co-products” to make economics work; This limits scale

Biofuels in a Petroleum Context



Source: Analysis based on information from IEA, DOE and interviews with super-majors

Losses in Biofuels



Zhu et al. *Current Opinion in Biotechnology* (2008) 19:153-159

Photosynthesis:

$$CO_2 + H_2O \Rightarrow C_6H_{12}O_6$$

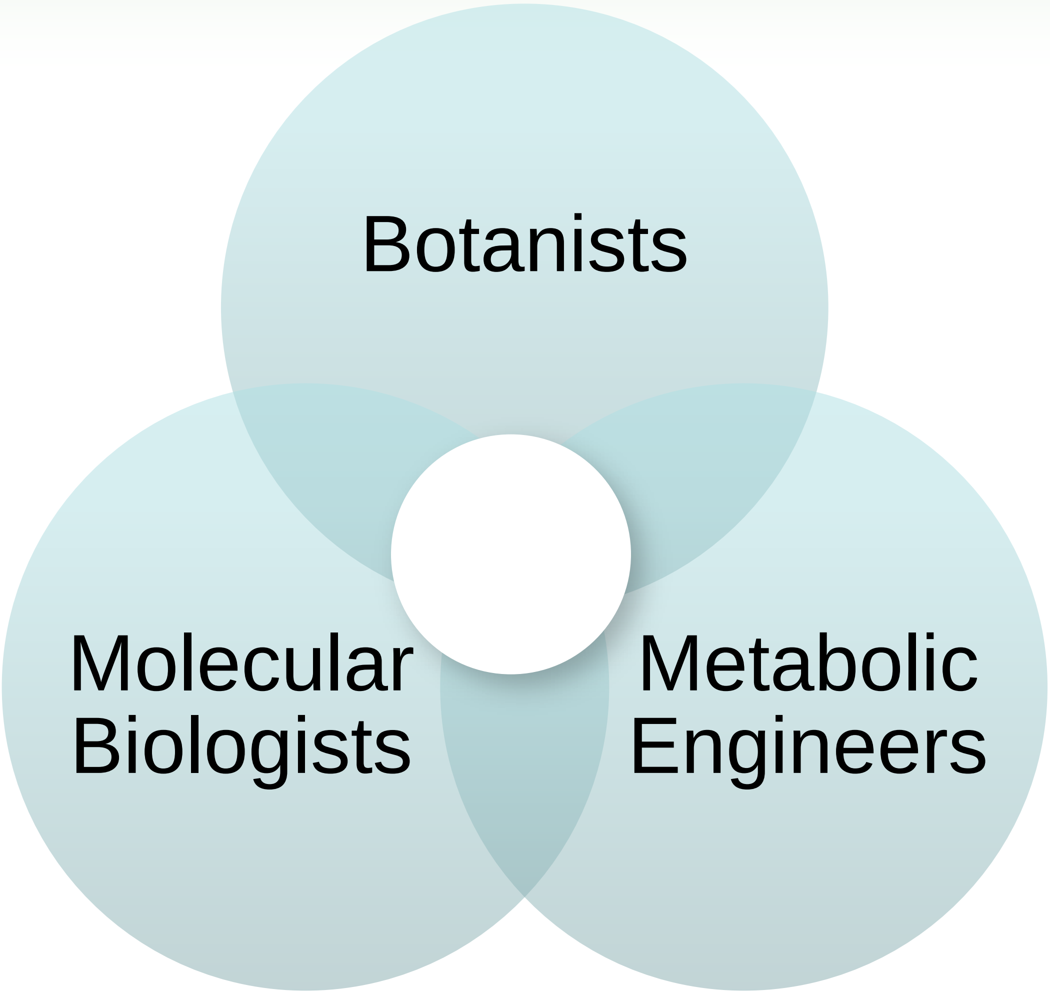
Fermentation:

$$C_6H_{12}O_6 \Rightarrow 2CO_2 + 2\ C_2H_5OH$$

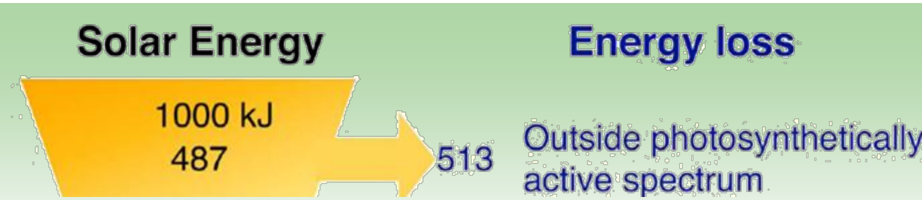
One third of the carbon captured is *not* converted into fuel.

In many regimes, carbon is *a limiting reagent*

White Space?

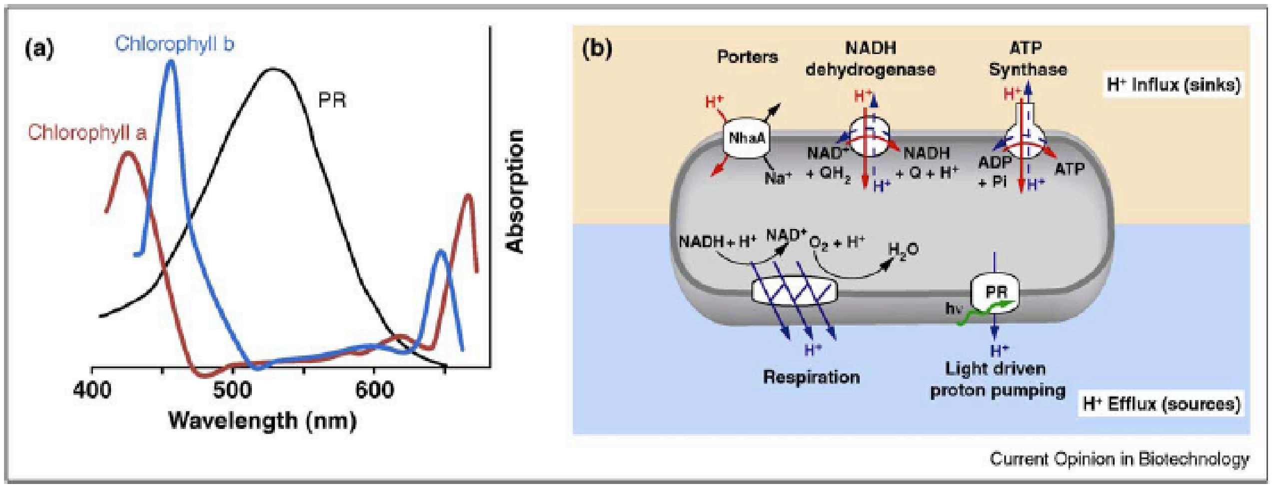


Absorption Engineering



- Proteorhodopsin
  - Novel Photosynthetic Pigment
  - Identified in seawater
  - Absorbs where Chlorophyll doesn’t

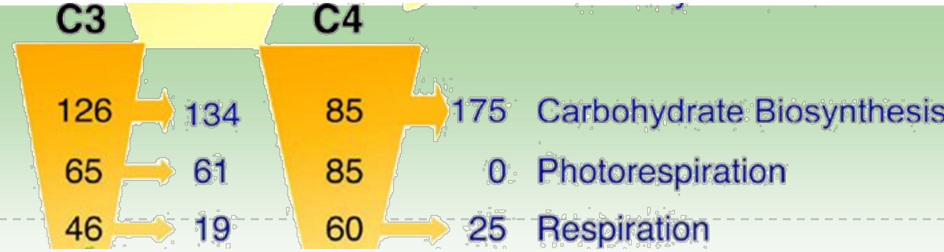
Figure 2



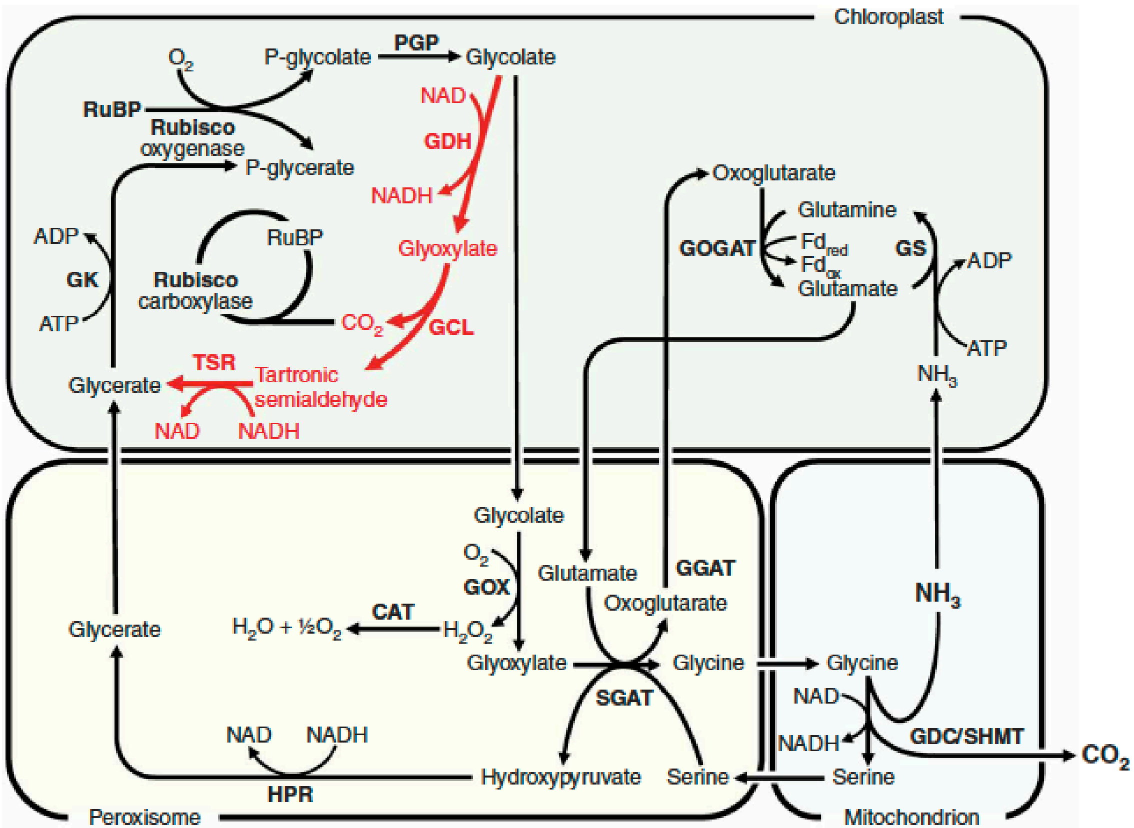
(a) Comparison of the absorption spectra of chlorophylls and proteorhodopsin (PR) shows that PR fills a gap in the chlorophyll absorption spectrum. Chlorophyll data from Mackinney [42]. **(b)** Schematic representation of enzymes and complexes generating and utilizing proton motive force. PR will be of particular use in conditions or processes where the pmf is low and key enzymatic reactions are ATP-limited or pmf-limited. Pmf can be supplied by oxidative phosphorylation or proton pumping by PR and drives many processes including ATP production, ion transport, and conversion of NAD^+ to NADH.

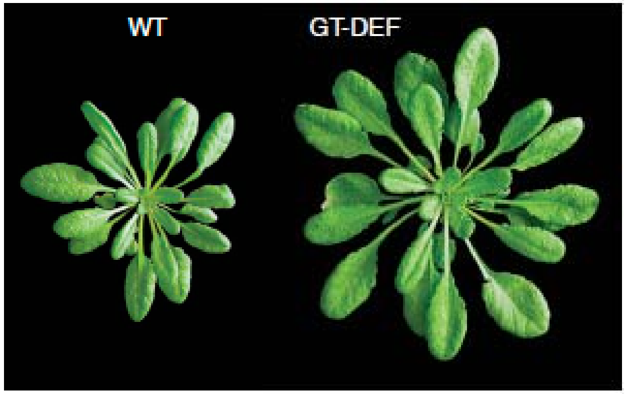
Walter et al., *Current Opinion in Biotechnology* (2010) 21:265–270

Metabolic Engineering



- Photorespiratory bypass
  - PG recycling from *E. coli*

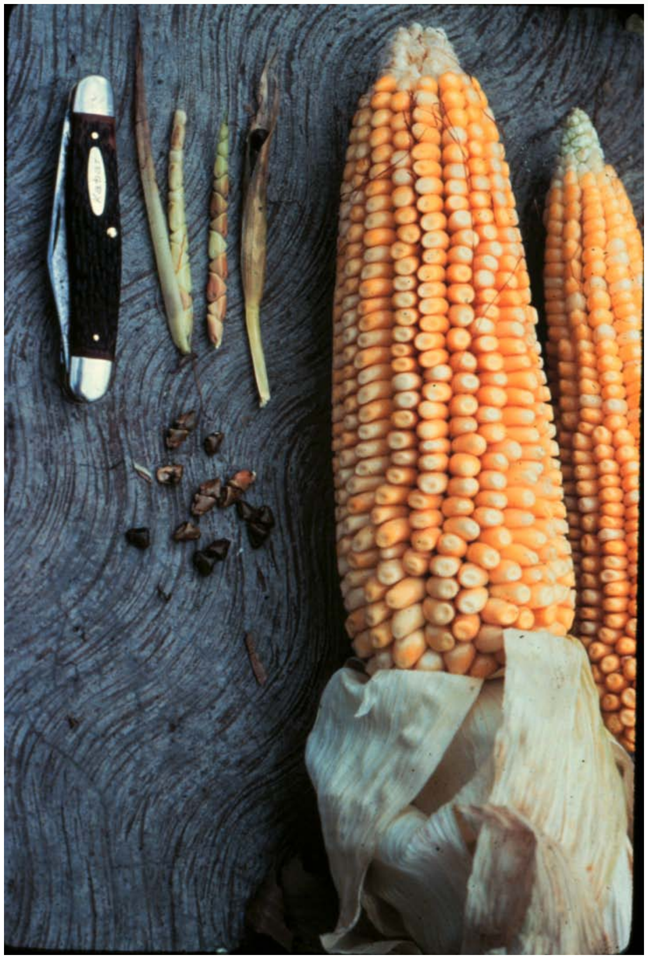




Kebeish et al., *Nature Biotechnology* (2007) 25: 593

Rapid conventional genetics

Actual:
- C_3 ~0.7% (avg), 2.4% (max)
- C_4 ~1.2% (avg), 3.7% (max)



Teosinte-to-maize

- Human-applied breeding required 9,000 years, countless individual selection steps
- Today, rapid genetic combinatorial experiments can accelerate optimization of field crops

The New York Times

November 16, 2010

Mutation Advances Set to Flip Biotech Crop Debate

By PAUL VOOSEN

Earlier this year, out in the remote test farms of North Dakota, researchers sprayed weedkiller on canola, a delicate golden-flowered plant used for cooking oil. A touch of the herbicide would have killed most plants, but the canola refused to wilt. It survived to late summer harvest.

Workshop Agenda Overview

Brief Technical Talks

Don Ort (UIUC)
"What is the maximum efficiency that photosynthesis can convert solar energy into biomass"

Tasios Melis (UC Berkeley)
"Photosynthesis to Fuels"

Ganesh Kishore (Former CTO, DuPont Ag, Chief Biotechnologist, Monsanto)
"What it takes to feed and fuel the world"

Morning Breakout Sessions – *Technology Barriers & Opportunities*

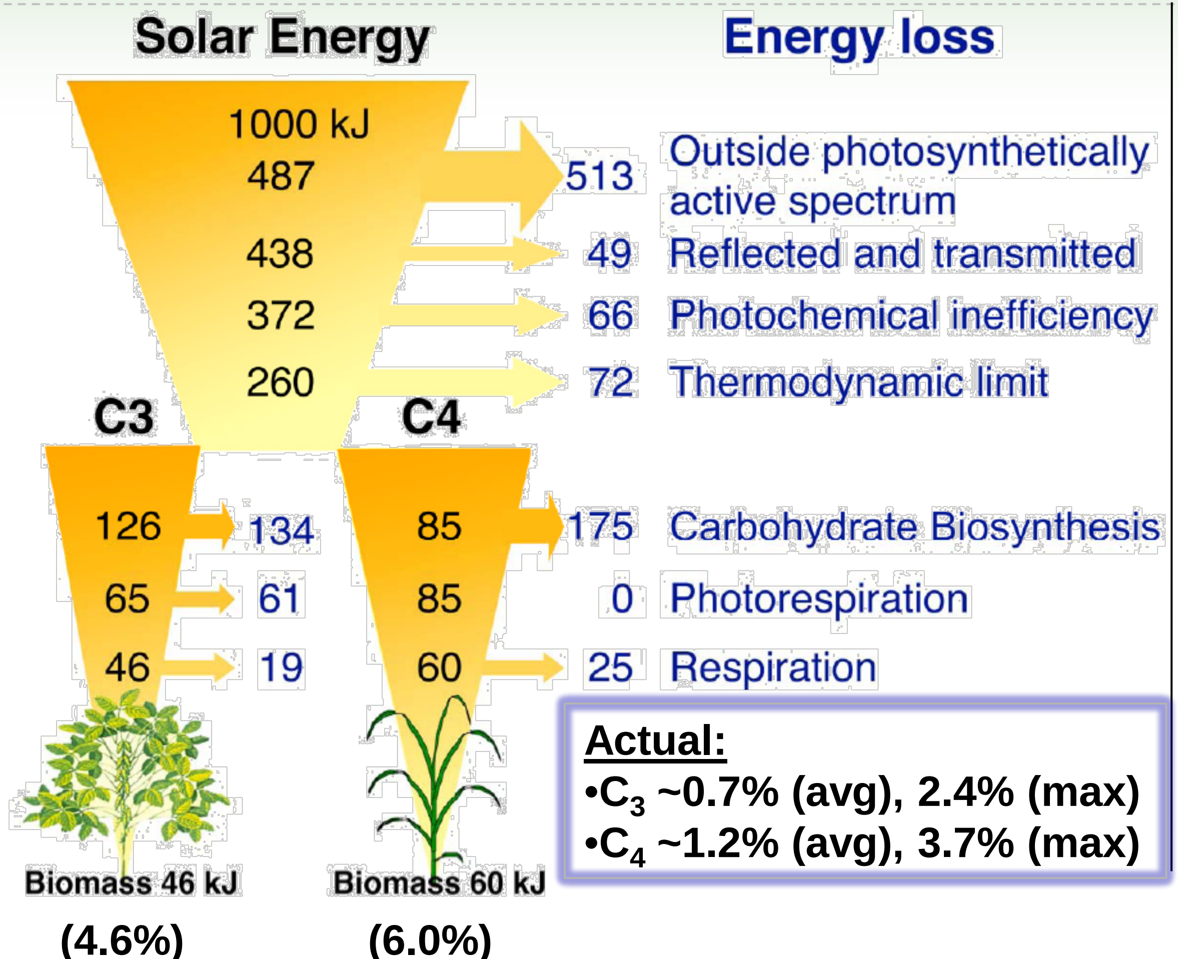
- Productive Light Absorption
- Metabolic Engineering
- Exploiting Evolution

Afternoon Technical Improvisation Sessions – *What would you create?*

- C_4 Plant
- Aquatic Phototroph
- "Model" Organism

Dec 3 (AM) – "Lessons Learned," Wrap-up

Plants



Actual:
- C_3 ~0.7% (avg), 2.4% (max)
- C_4 ~1.2% (avg), 3.7% (max)

Opportunities exist to raise the conversion efficiency (ε_c) of photosynthesis:

- Re-engineer RuBisCO (≤ 25% increase in C_3 ε_c)
- Bypass photorespiration (≤ 13% increase in C_3 ε_c)
- Convert C_3 plants to C_4 (≤ 30% increase in C_3 ε_c)
- Design photosystems with two different action spectra (increase in ε_c?)

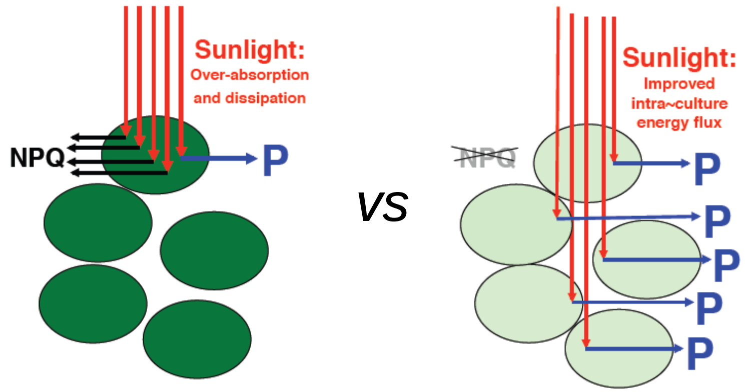
D. Ort presentation

The same fundamental principles drive aquatic and land-based photosynthesis: Photosynthesis is not inherently more efficient in any organism.

Aquatics

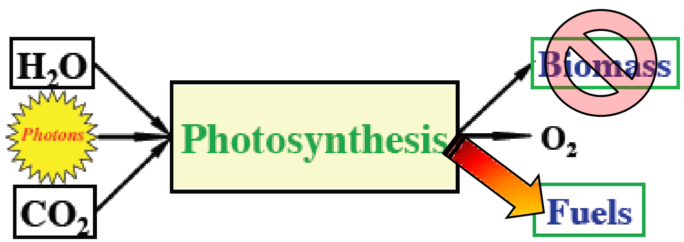
Two-dimensional problem in light utilization:

1) Sunlight is wasted by organisms near the surface, starving bulk



2) It may be possible to extend productive absorption from 700 to 950nm

Carbon partitioning between biomass and fuel must be addressed:



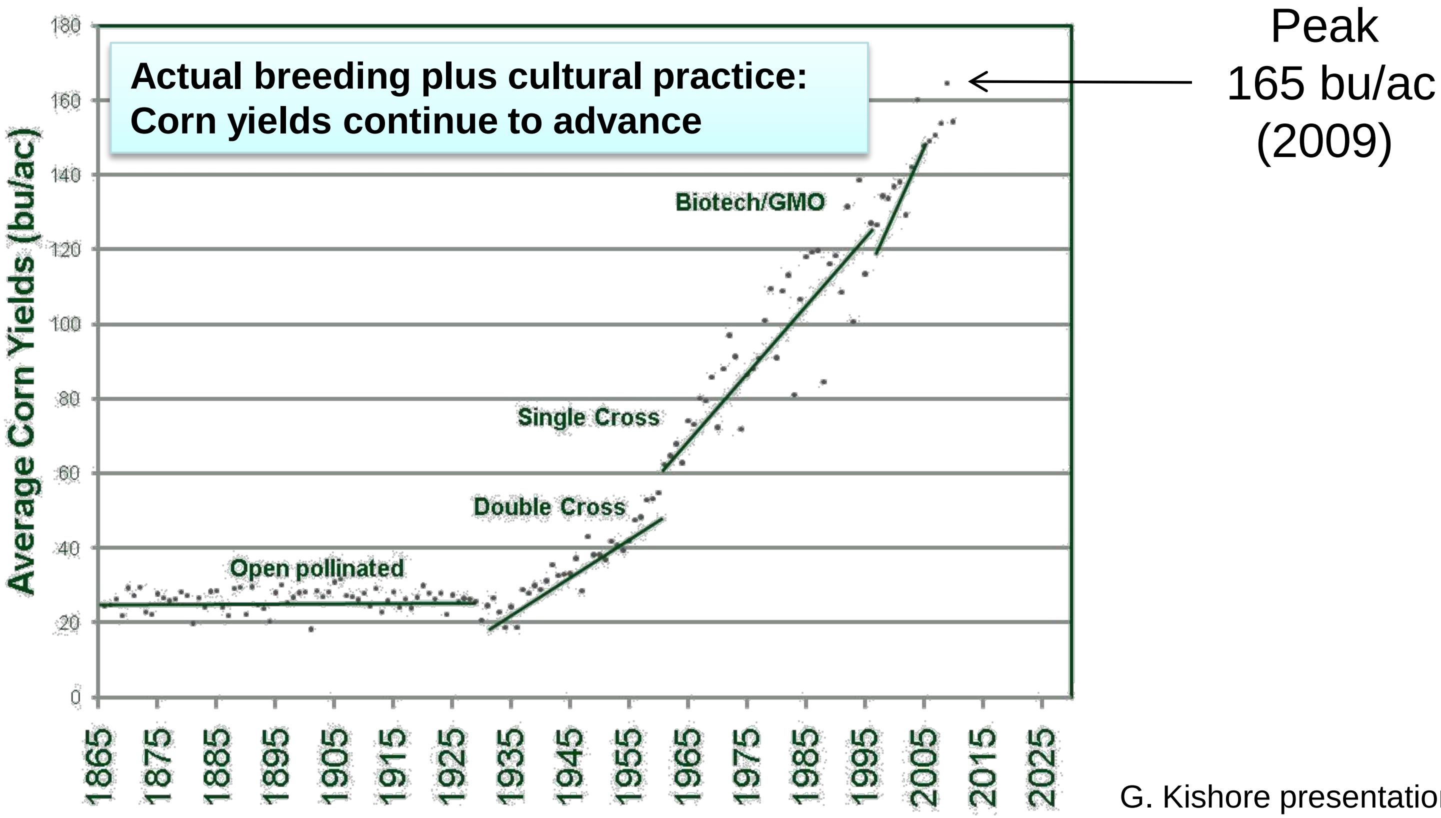
Fuel-to-biomass is low

Tools needed: metabolic engineering, technologies for chloroplast engineering

T. Melis presentation

Agronomics

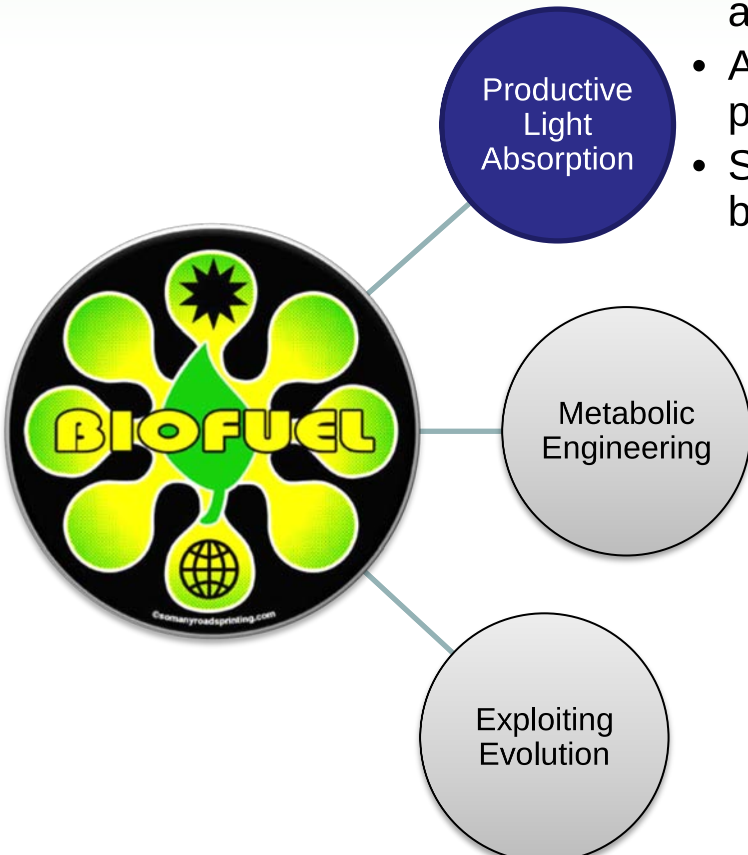
- Technology to meet global demands for food *and* energy production is available, but untapped
- Productivity comes from selection, plus optimum nourishment of crops
- All agriculture is local – there is no “one size fits all” solution



G. Kishore presentation

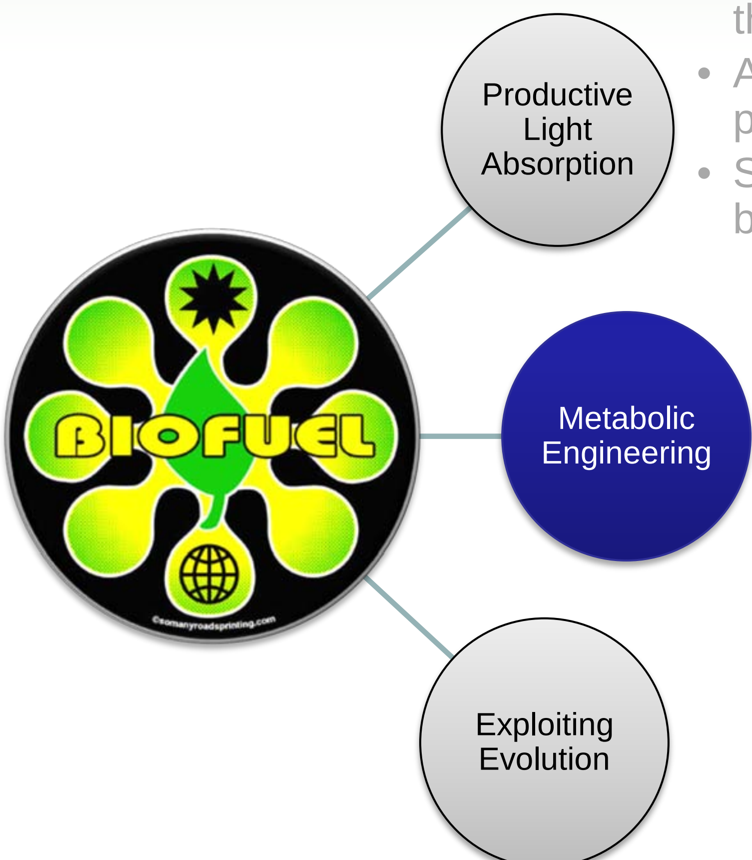
Following A.F. Troyer, Crop Sci. 46:528–543 (2006).

Needs Identified



- Computational Tools (CAD) to model the flux balance and the physics of cells
- A standardized way to evaluate and rank all the potential variable changes
- Screening tools to develop a library of modules that can be mixed and matched in organism development

Needs Identified



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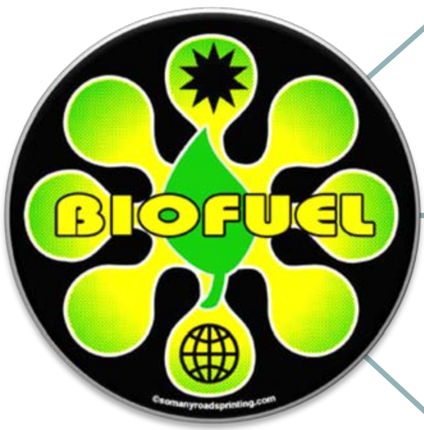
- Targeted research (non-basic) in gene regulation, expression mechanisms, and silencing
- Modeling of energy and carbon fluxes, feedback mechanisms, metabolism in “hybrid” genomes
- Combinatorial approach to engineering pathways
- Stationary isotopic labeling for plants

Needs Identified



Productive Light Absorption

- Computational Tools (CAD) to model flux balance and the physics of cells
- A standardized way to evaluate and rank all the potential variable changes
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Metabolic Engineering

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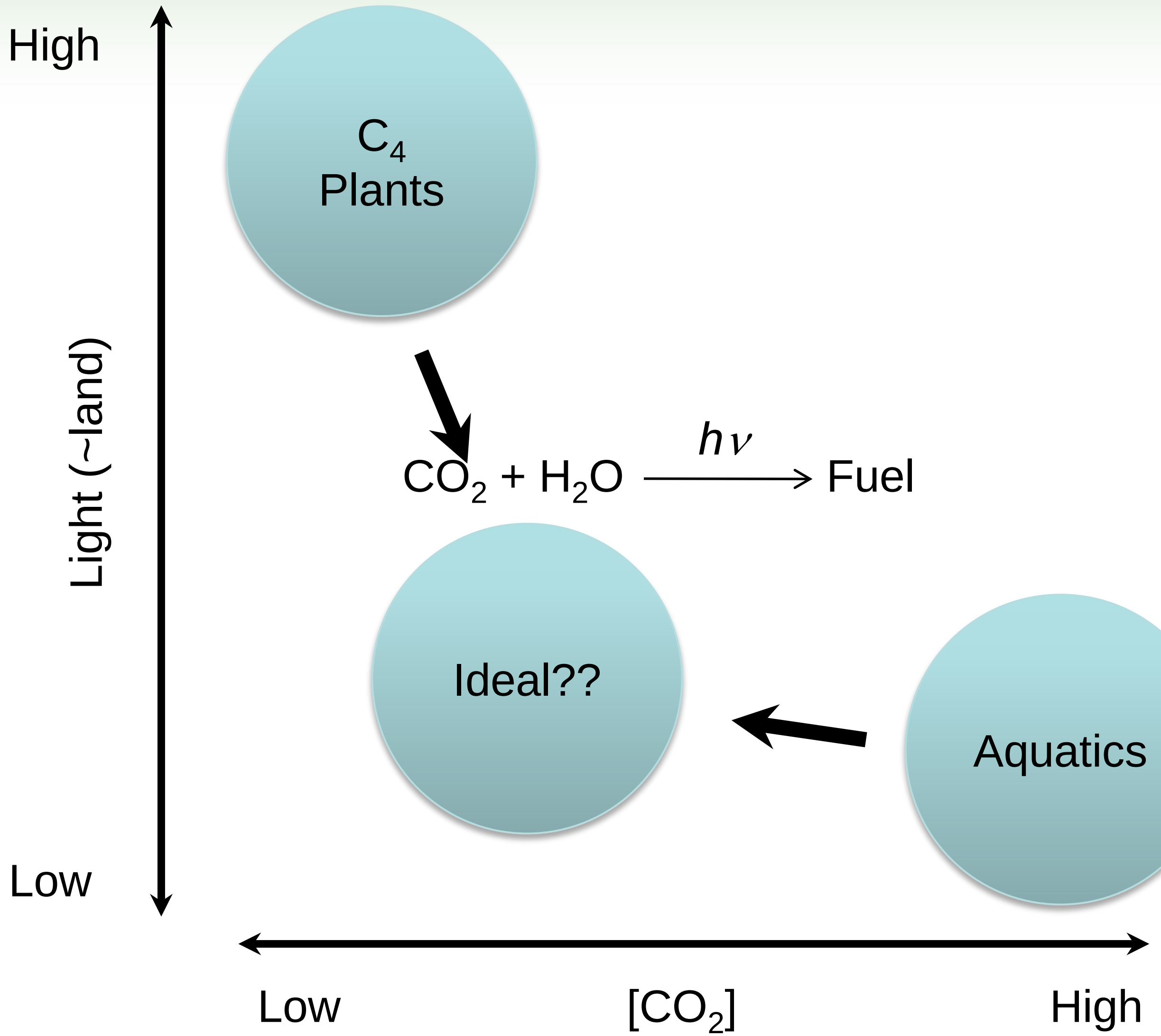
Exploiting Evolution

- Selection schemes/platforms that are not organism or gene specific
- Metagenomic studies for gene, allele discovery
- Next generation sequencing to discover the existing genetic diversity (as in pharmacogenomics)
- Faster phenotyping
- Metabolome profiling for different plant parts

Workshop Outcomes

- **Our take-aways**
  - Focus on systems approaches, not theoretical/component improvements
  - Measure carbon yield (t_C/ha·yr), not energy efficiency (E_{out}/E_{in})
  - Interdependent system implies interdisciplinary breakthroughs. Combine:
    - *Light Productivity to fix more carbon*
    - *Metabolic Engineering/Modeling to divert more carbon to product*
    - *Evolution/Crop Genetics to optimize for field deployment*
  - Algae (cyanobacteria) advances may guide chloroplast modifications
  - Agriculture is regional. Choose strategies over specific solutions
- **Open issues**
  - Should a fuel molecule be chosen?
  - Which approaches are likely to bear fruit the soonest?

Framing the Issues



Carbon efficiency in corn grain ethanol production

$4.4\ t_C \cdot ha^{-1} \cdot y^{-1}$

$3.0\ t_C \cdot ha^{-1} \cdot y^{-1}$

$\sim 8.5\ t_C \cdot ha^{-1} \cdot y^{-1}$

<u>Overall Carbon Yield</u>

3.4 %

<u>Overall Fuel Yield</u>

90 $GJ \bullet ha^{-1} \bullet y^{-1}$

$1.7\ t_C \cdot ha^{-1} \cdot y^{-1}$

EtOH Energy Content: 52 $GJ \bullet t_C^{-1}$

Carbon efficiency in soybean biodiesel production

~2.2 $t_C \cdot ha^{-1} \cdot y^{-1}$

1.5 $t_C \cdot ha^{-1} \cdot y^{-1}$

0.46 $t_C \cdot ha^{-1} \cdot y^{-1}$

0.37 $t_C \cdot ha^{-1} \cdot y^{-1}$

FAME Energy Content: 50 GJ•t_C^{-1}

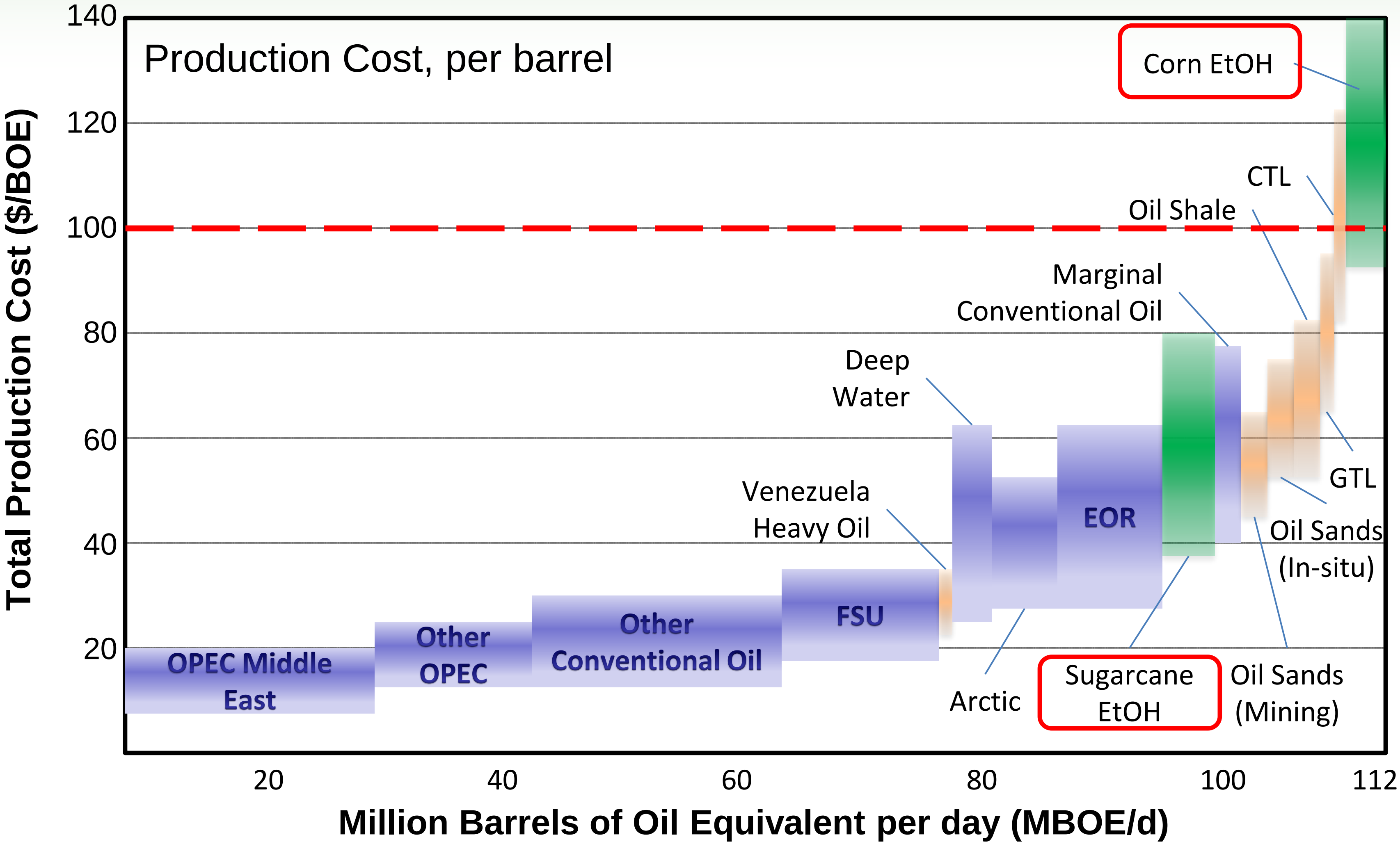
Overall Carbon Yield
0.74 %

Overall Fuel Yield
18 GJ•ha^{-1}•y^{-1}

Carbon efficiencies

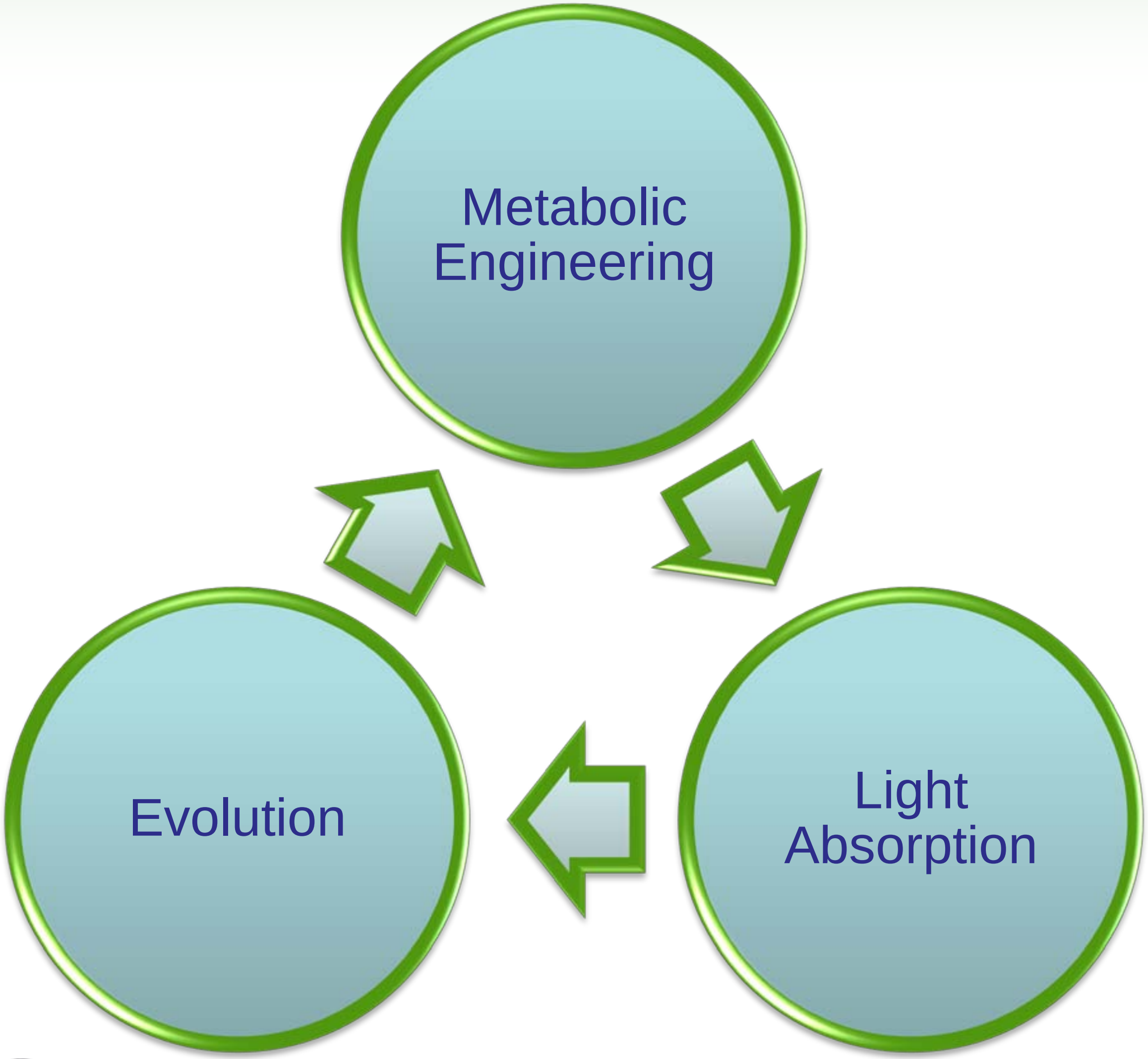
Source	Yield	
	Carbon	Liquid Fuel $GJ \bullet ha^{-1} \bullet y^{-1}$
Cane	5.6%	140.
Maize	3.4%	90.
Switchgrass	2.2%	57.
Soybean	0.74%	18.

Biofuels in a Petroleum Context



Source: Analysis based on information from IEA, DOE and interviews with super-majors

Synergies



Workshop Output Report

Visit: www.arpa-e.energy.gov

Click: “Events & Workshops”

Click: “Past Workshops”

Applied Biotechnology for Transportation Fuels

Thursday, December 02, 2010 - Friday, December 03, 2010

ARPA-E hosted an event in its public workshop series – “Applied Biotechnology for Transportation Fuels: Meeting Today's Energy Needs by Maximizing Photon Capture,” on December 2-3, 2010, in Arlington, Va. The workshop brought together thought leaders from distinct science and engineering communities to develop new ideas and identify practical approaches toward increasing the efficiency of light collection by biological systems and the conversion of that energy into liquid forms of chemical energ...

Read More Workshop Output